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ACCURATE MASS MEASUREMENTS OF SHORT-LIVED ISOTOPES WITH THE *MISTRAL*[*] RF SPECTROMETER

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Abstract. The *MISTRAL*[*] experiment has measured its first masses at *ISOLDE*. Installed in May 1997, this radiofrequency transmission spectrometer is to concentrate on nuclides with particularly short half-lives. *MISTRAL* received its first stable beam in October and first radioactive beam in November 1997. These first tests, with a plasma ion source, resulted in excellent isobaric separation and reasonable transmission. Further testing and development enabled first data taking in July 1998 on neutron-rich Na isotopes having half-lives as short as 31 ms.

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[*]Mass measurements at ISolde using a Transmission RAdiofrequency spectrometer on-Line

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The atomic mass is a global property that can elucidate interesting physics from the binding energy. Atomic physics requires particularly high accuracy mass measurements in order to isolate contributions beyond those accounted for by quantum electrodynamics [1,2] as does any effort at verifying fundamental symmetries between, for example, particles and their anti-particles [3].

The interest in measuring masses of radioactive isotopes comes from an ever-present need to understand the nature of the nuclear force. The topography of the mass surface gives us clues to the nature of nuclear structure. As we climb either side of the so-called valley of stability, we expect the landscape to become more and more exotic out to the point where a nuclear configuration reaches saturation at the cliffs of nuclear particle stability that are called the drip lines.

The mass difference of isotopes involved in a nuclear reaction can also provide constraints on the nature of the involved interaction, radioactive β-decay being of particular interest as it is the signature of the weak interaction [4,5].

Finally, knowledge of the nuclear binding energy is extremely important for nucleosynthesis, in particular the rapid neutron capture process, thought to occur in exploding supernovae. Masses are required to calculate a variety of physical quantities involved in this process and to reproduce the abundances of the heavy elements present in the solar system [6].

MISTRAL is one of several programs dedicated to the accurate mass measurement of radioactive isotopes. These programs are all complementary in technique and/or applicability. Cyclotrons that accelerate reaction products allow us to reach far up into the cliffs of exotic nuclei [7] and storage rings offer nuclear lifetime measurements as an added bonus to huge mass harvests from high energy fragmentation reactions [8]. Penning traps offer a kinder and gentler environment for mass measurements and consequently hold the records for accuracy [9,10]. The key here is that a single ion may be held for as long as necessary to make a measurement. *ISOLTRAP*, a Penning trap spectrometer on-line at *ISOLDE*, has its accuracy slightly compromised by the adverse on-line conditions and connection to the outside world but nevertheless provides excellent and systematically accurate measurements of radioactive isotopes [11].

The *MISTRAL* spectrometer, also at *ISOLDE*, is a sort of hybrid between a cyclotron and a Penning trap. Its rather special technique of radiofrequency excitation of the cyclotron motion at the full beam transport energy allows very rapid measurements of high accuracy thus rendering it particularly suitable for short-lived isotopes [12,13]. Thus, *MISTRAL* complements *ISOLTRAP* which must store ions for longer periods in order to make a very accurate measurement.

A schematic diagram of the *MISTRAL* spectrometer with its nominal trajectory is shown in figure 1. Ions injected at the full *ISOLDE* beam energy (60 kV) follow a two-turn helicoidal trajectory inside the annular, homogeneous magnetic field (figure 1, inset center) and are counted using a secondary electron multiplier. With an injection slit size of 0.4 mm and orbit radius of 0.5 m, a mass resolution of 2500 is obtained using no radiofrequency. In order to make a measurement, a longitudinal kinetic energy modulation is effected using two symmetric electrode structures (figure 1, inset right) located at the one-half and three-half turn positions inside the magnetic field. This way the ions make one cyclotron orbit between the two modulators. A radiofrequency voltage is applied to the central modulator elec-

trodes. Depending on the phase of this voltage when the ions traverse the structure, the resulting longitudinal acceleration produces a larger or smaller cyclotron radius than that of the nominal trajectory (all the trajectories are isochronous). The ions are transmitted through the 0.4 mm exit slit when the net effect of the two modulations is zero. This happens when the radiofrequency voltage is an integer-plus-one-half multiple of the cyclotron frequency which means that during the second modulation the ions feel exactly the opposite of what they felt during the first. For high harmonic numbers (e.g. larger than 1000) and a radiofrequency voltage of about 200 V, the ion signal over a frequency scan shows narrow transmission peaks having resolutions of up to 100,000 evenly spaced at the cyclotron frequency (figure 1, inset left).

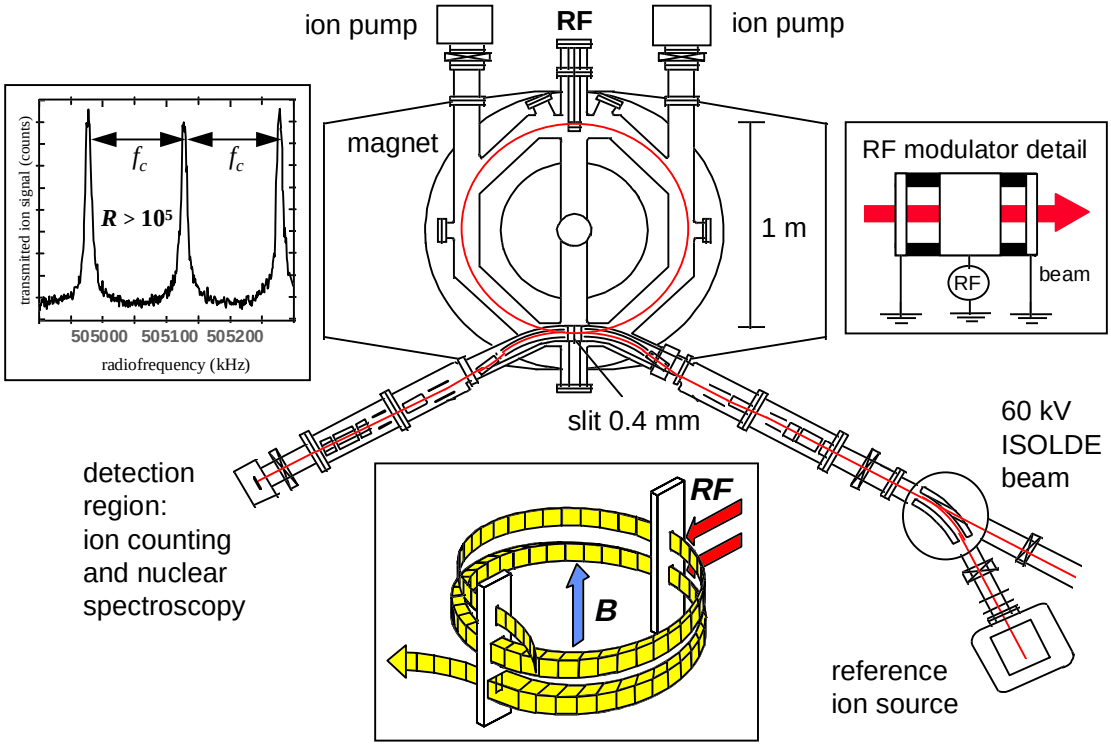

FIGURE 1. Layout of the MISTRAL spectrometer showing the nominal ion trajectory. Ions are injected from the *ISOLDE* beam line at the full transport voltage of 60 kV while the reference mass is alternately injected (without changing the magnetic field) at its required (lower) energy. Inset (right) shows the modulator electrode structure the geometry of which is selected depending on the mass range of operation. Inset (center) shows an isometric view of the trajectory envelope with the 0.4 mm injection slit followed by the first modulator at one-half turn, the phase-definition slit (up to 5 mm wide to incorporate the envelope of cyclotron radii), the second modulator at three-half turns and finally the exit slit. Inset (left) shows the transmitted ^{39}K ion signal as a function of radiofrequency spanning three harmonic numbers (around 3400). The mass resolution is greater than 100,000.

A mass measurement is made when an unknown mass is alternately injected with a reference mass. These comparisons are done in rapid succession (seconds) in order to eliminate short-term drift in the magnetic field. Comparing masses in this way, without changing the magnetic field, requires changing not only the transport energy of the reference beam but the voltages of all electrostatic elements in the spectrometer (two triplets, eight pairs of steering plates, and two benders plus the injection switchyard bender). Since, for the moment, the reference ion source does not withstand more than 60 kV, we are obliged to use a reference mass that is heavier than the ISOLDE mass in order to operate ISOLDE and its transport system at the nominal voltage. A reference source upgrade later this year should avoid this limitation for future runs.

ISOLDE uses a pulsed proton beam extracted from a set of synchrotron booster rings [14]. In the case of short-lived isotopes (as well as elements with very rapid release times from the target matrix, such as Na) it is impossible to scan the entire required frequency range in time after the impact of the proton pulse. In this case, a special acquisition mode is used (called, appropriately: point-by-point). For each radioactive beam pulse, the ion transmission signal is recorded for only one radiofrequency point (determined randomly) and the resonance peak is reconstructed at the end. This mode not only allows us to increase statistics in the peak but for each point, the ion signal is recorded with the radiofrequency switched off so that not just the intensity but the true transmission is measured.

The *MISTRAL* spectrometer was installed in the new beam hall extension of *ISOLDE* in mid-1997 and a first test run using radioactive isotopes around $A = 27$ took place at the end of that year using a UC_2 target coupled with a plasma ion source. The spectrometer was able to cleanly separate the isobaric components with relatively good sensitivity and very encouraging indications for measurement precision.

In July 1998, *MISTRAL* again took radioactive beam from a UC_2 target but this time coupled to a surface ionization source to get a clean beam of Na isotopes. This element is nevertheless very challenging since the release time from the target matrix is very fast so the measurements are made using the point-by-point mode described above.

During this run we were able to measure the masses of $^{23\text{-}30}$Na. Shown in figure 2 is a recorded (reconstructed) peak for ^{28}Na. This measurement corresponds to 64 (random) frequency steps of 320 ms each. Each step is triggered by the PS booster proton pulse with a period of (at least) 1.2 s. The center frequency (derived from a triangular fit [15]) is about 480,050 kHz corresponding to harmonic number 2342 of the cyclotron frequency of ^{28}Na in the 0.37359 T field at a beam energy of 60 keV. The mass resolution in this case is 47,860.

When we compare our preliminary values to those in the mass table we perceive an offset (proportional to ΔM, the mass-doublet difference) of about $7 \times 10^{-7}/\Delta M$: the measurements are precise (reproducible, to 0.2 ppm) but not accurate. The mass uncertainties for the isotopes further from stability are naturally dominated by statistical error. If we correct this offset, the residual difference scatters randomly about zero within a value of about ±30 keV, a fairly good accuracy; already better than the present one for ^{28,29,30}Na ($T_{1/2}$ = 31, 45, 48 ms) and which will be certainly improved. The relatively large systematic error is due to a lack of congruency be-

tween the reference ion trajectory and that of the mass being measured. Ions of differing trajectories do not experience the same magnetic field because of residual gradients (~10^{-5}/cm). We plan to reduce these field gradients through the use of current shim coils [16].

A important point is the chronic problem of sensitivity - exotic nuclei are produced in such small quantities that it is a shame to waste a single ion! This problem can be tackled by the addition of a beam cooling device at the entrance of the spectrometer. By reducing the emittance of the incoming beams not only is the transmission through the many slits inside the spectrometer improved but both the reference and ISOLDE beam are "brainwashed" before they go through, forgetting their differing characteristic divergences, positions and energy spreads, so following the same path through the spectrometer. Cooling a beam can be done several ways but the one technique that seems the fastest and most universal makes use of a light, neutral buffer gas. We plan to install a gas-filled ion guide that will use the alternate focusing of a radiofrequency quadrupole field to continually refocus the ion beam onto the axis while it loses kinetic energy from collisions with the gas [17].

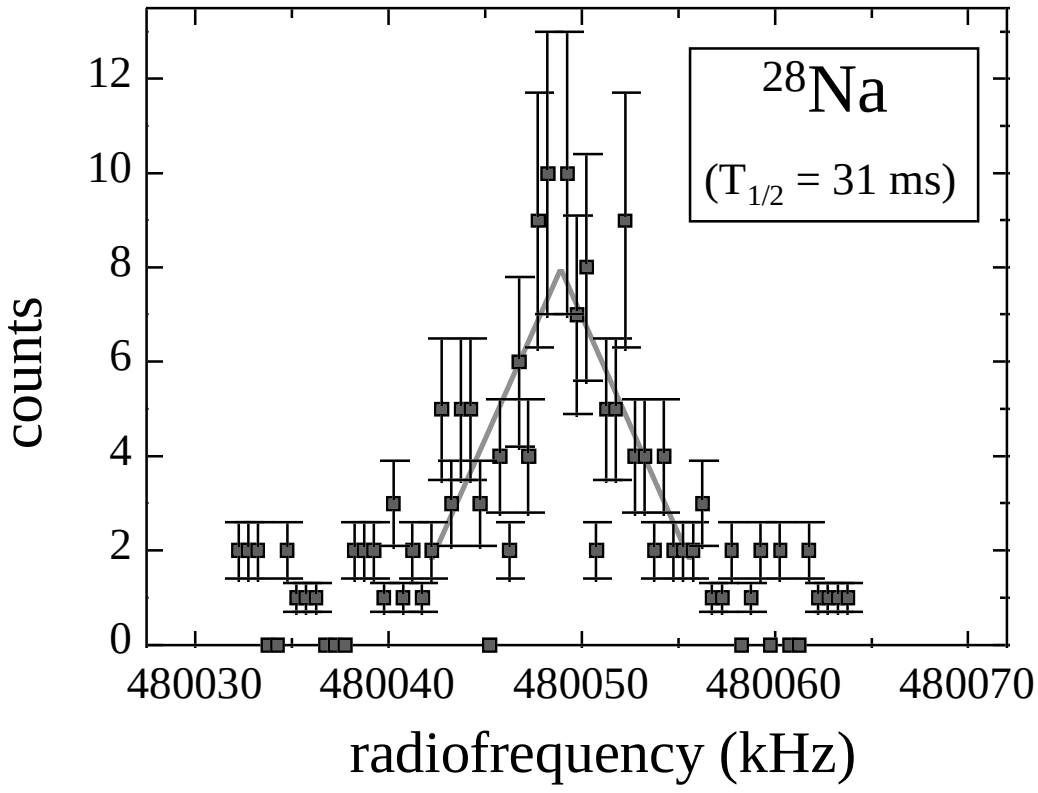

FIGURE 2. A recorded (reconstructed) peak for ^{28}Na ($T_{1/2}$ = 30.5 ms). This measurement corresponds to 64 (random) frequency steps of 320 ms each. The center frequency of about 480,050 kHz is derived from a triangular fit [15] and corresponds to harmonic number 2342 of the cyclotron frequency of ^{28}Na in the 0.37359 T field at a beam energy of 60 keV. The mass resolution is 47,860.

The potential measurement program at *ISOLDE* is quite rich. Though the calculated transmission of 1% has not yet been reached, there are some one hundred candidates for either new measurements or considerably reduced error. The next scheduled beam time for *MISTRAL* is November, 1998. In the longer term, we hope that the development of the ion cooler will extend our measurement possibilities with better sensitivity but also aid in reducing systematic error.

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REFERENCES

1. C. Carlberg *et al.*, this volume.
2. G. Soff, this volume.
3. G. Gabrielse *et al.*, this volume.
4. J. Byrne *et al.*, this volume.
5. J. Behr *et al.*, this volume.
6. B. Jonson, Physica Scripta T59 (1995) 53
7. M. Chartier *et al.*, this volume.
8. M. Steck *et al.*, this volume.
9. R. Van Dyke *et al.*, this volume.
10. S. Rainville *et al.*, this volume.
11. G. Bollen *et al.*, this volume.
12. D. Lunney *et al.*, Hyperfine Interactions 99 (1996) 105
13. M. de Saint Simon *et al.*, Physica Scripta T59 (1995) 406
14. J. Lettry *et al.*, Nucl. Instr. and Meth. B 126 (1997) 130
15. A. Coc *et al.*, Nucl. Instr. and Meth. A 271 (1988) 512
16. A. Coc *et al.*, Nucl. Instr. and Meth. A 305 (1991) 143
17. S. Henry *et al.*, this volume.